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Neutron Star Science with the NuSTAR

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LDRD FINAL REPORT

Neutron Star Science with NuSTAR

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Abstract

The *Nuclear Spectroscopic Telescope Array* (*NuSTAR*, Figure 1), launched in June 2012, helped scientists obtain for the first time a sensitive high-energy X-ray map of the sky with extraordinary resolution. This pioneering telescope has aided in the understanding of how stars explode and neutron stars are born. LLNL is a founding member of the *NuSTAR* project, with key personnel on its optics and science team. We used *NuSTAR* to observe and analyze the observations of different neutron star classes identified in the last decade that are still poorly understood. These studies not only help to comprehend newly discovered astrophysical phenomena and emission processes for members of the neutron star family, but also expand the utility of such observations for addressing broader questions in astrophysics and other physics disciplines. For example, neutron stars provide an excellent laboratory to study exotic and extreme phenomena, such as the equation of state of the densest matter known, the behavior of matter in extreme magnetic fields, and the effects of general relativity. At the same time, knowing their accurate populations has profound implications for understanding the life cycle of massive stars, star collapse, and overall galactic evolution.

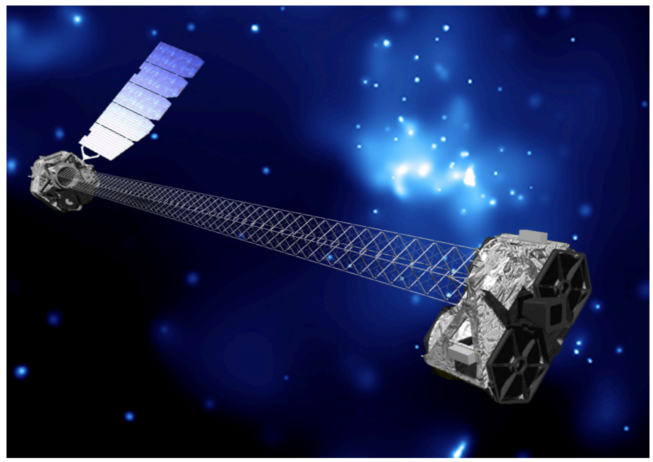

Figure 1 The *Nuclear Spectroscopic Telescope Array* consists of two focusing hard X-ray optics connected to the CdZnTe focal plane detectors by a 10 m long extendable mast.

With this project we identified new behavior of neutron stars, tested model predictions and advanced our understanding of these complex celestial objects. Proper interpretation of *NuSTAR* observations requires appropriate models of telescope and detector performance and knowledge of how *NuSTAR* instruments modulate the intrinsic X-ray emission. Our research is of great interest to the astrophysics community and provided LLNL with a leading presence in X-ray astronomy and astrophysics, therefore facilitating Laboratory participation in next-generation experiments.

Background and Research Objectives

During the last decades, observational astronomy has expanded from the relatively narrow wavelength band of visible light to the entire electromagnetic spectrum. X-ray astronomy, covering the band of photon energies from 0.1 keV to several 100 keV, belongs to one of the most flourishing of these newly opened spectral ranges. X-ray observations provide insight to phenomena, which occur at the end of stellar life: supernova explosions, neutron stars (NSs), and black holes. They can also address questions of cosmological consequences like determining the nature of dark matter. While several missions have studied the sky in soft X-rays (below 10 keV), *NuSTAR* (Harrison et al. 2013), a NASA mission launched in June 2012, provided the first high-sensitivity observations of the hard X-ray sky up to 80 keV. These data have given us the unique opportunity to study a wealth of new astrophysical phenomena.

Even though NSs were postulated in 1934 (Baade & Zwicky 1934) and first detected in 1967 (Hewish et al. 1968, Nobel Prize in 1974), our knowledge of these enigmatic end-points of stellar evolution is still very limited. Soft X-ray studies have discovered that there are many more members of the NS family than just accretion-powered sources or rotation-powered pulsars (RPPs, also known as radio pulsars). These new “cousins” identified during the last decade include magnetars and high-B field pulsars (Kaspi 2010) and are still a mystery to astrophysicists. Hard X-ray studies not only help understand the newly-discovered astrophysical phenomena and emission processes, but they also expand the utility of NS observations for addressing broader questions in physics. For example, NSs provide an excellent laboratory to study exotic and extreme physical phenomena due to (1) their high densities of a few 10^{14} g/cm^3 (studies of equation of state of the densest matter known), (2) their extreme magnetic fields of up to 10^{15} Gauss (behavior of matter in extreme magnetic fields), and (3) effects of general relativity (Nobel Prize in 1993). At the same time, knowing their accurate populations has profound implications for understanding galactic evolution.

The unprecedented sensitivity of *NuSTAR* arises from its use of solid state detectors and focusing multilayer optics, the first time such telescopes have been used for hard X-ray astronomy. With its high sensitivity in the X-ray region, *NuSTAR* is perfectly suited to study the behavior of NSs. The hard X-ray regime is especially interesting since certain phenomena begin (or cease) to become the dominant emission mechanism and the physical extent of NS emission is expected to vary with energy. Quantifying these properties requires exquisite knowledge of *NuSTAR*'s response.

The main objective of this project was the study of magnetars and high-B rotation-powered pulsars (RPPs). Young, isolated NSs with an extremely powerful internal magnetic field are known as magnetars. This class of NSs is assumed to be powered by the decay of their inner intense B fields (10^{14}-10^{15} G), which leads to their violent outbursts of X-ray emission. Both the physics of magnetars and their origin are still not well understood. While they were long considered to be soft X-ray sources (mainly emitting below 10 keV) with spectra well described by a thermal component plus a hard power-law tail, *INTEGRAL* (Winkler et al. 2003) recently detected persistent hard X-ray emission from magnetars. While below 10 keV the spectra of different subgroups of magnetars exhibit different hardness, *INTEGRAL* and subsequently *RXTE/HEXTE* (Bradt et al. 1993) made the surprising observation that the spectra change dramatically in the harder X-ray regime. The sudden upturn in the magnetar spectra between 10-20 keV still remains puzzling, as does the change in the relation of relative hardness for different types of magnetars: at higher energies (> 10 keV) some magnetar spectra hardly change while those for other magnetar-subtypes become harder. While this behavior is not yet understood, it appears to be crucial in comprehending magnetars, since they emit mostly above 10 keV. Recent models addressing the hard X-ray emission from magnetars have been tested with *NuSTAR* and the mission has constrained the properties of the NS magnetosphere in this extreme high-field environment.

Our secondary objective was using *NuSTAR* to study pulsar wind nebulae (PWNe), which result from the interaction of a RPP with its surroundings. These PWNe, which are only observable from NSs with high spin-down luminosities, emit X-rays when a relativistic outflow of particles from the NS is confined, and subsequently, shocked by nearby material. The most well-known PWN is the Crab nebula, which is visible, both in the optical and X-ray. A *Chandra* image of the Crab is shown in Figure 2 (left) along with another famous PWN, PSR B1509-58, nicknamed the "Hand of God" (Figure 2, right; *Chandra*/*NuSTAR* data). *NuSTAR* has provided significant observational constraints and advanced our knowledge of fundamental pulsar physics.

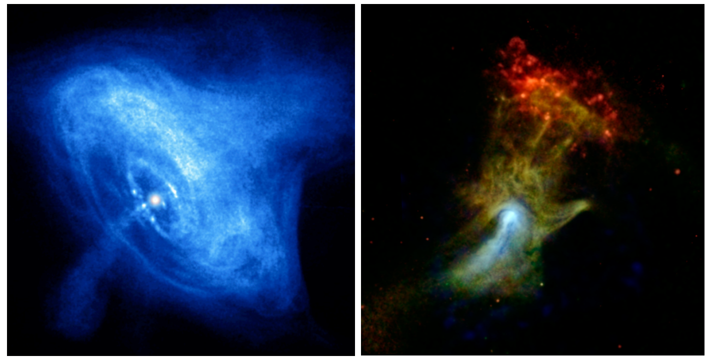

Figure 2 PWNe observed in X-rays. Left: *Chandra* view of the Crab nebula with its toroidal morphology and jet structure (NASA/CXC/SAO). Right: The PSR B1509-58 pulsar wind nebula, known as "Hand of God", as seen by *Chandra* (red: 0.5-2 keV, green: 2-4 keV) and *NuSTAR* (blue: 7-25 keV) (NASA/JPL-Caltech/McGill).

Additional objectives (funded through augmentations to the project) included *NuSTAR* calibration efforts (FY13) and the study of solar observations to search for axions (dark matter candidates) in FY15.

All studies of pulsars with *NuSTAR* require exquisite knowledge of the behavior for its telescopes in terms of throughput and point-spread function, especially as a function of energy and off-axis position. The LDRD team has been in a unique position to perform this work as member of the NuSTAR optics team possessing the detailed knowledge of both the telescope models and simulation tools that we helped develop. The goal of the calibration was to compare on-orbit calibration data to the physics-based models, to understand the discrepancies between the two (> 20%) and ultimately to improve the model to describe the observations.

The second additional objective was the search for solar axions with *NuSTAR*. Axions are - together with Weakly Interacting Massive Particles

(WIMPs) - favored dark matter candidates able to account for about 25% of the mass in the universe and *NuSTAR* provides a complimentary approach to conventional axion search experiments. Initial *NuSTAR* solar observations in search for nanoflares establish observational criteria for dedicated axion measurements using the satellite.

Scientific Approach and Accomplishments

In order to identify new behavior of NSs, proving or refuting model predictions and advancing our understanding of these complex objects, preparatory work included contributions to the *NuSTAR* calibration as well as the development of algorithms for NS data analysis, the testing of these codes on archival data and observational preparations, such as target selection. Once *NuSTAR* had acquired relevant data, the full analysis process comprised data processing, scientific interpretation and comparison of results with latest theoretical predictions. Our team analyzed and published data for three high-B RPPs (archival data from *XMM-Newton*/*Chandra*) and five *NuSTAR*-observed NSs (4 magnetars, one RPP/PWN) with additional (simultaneous and/or archival) soft X-ray data. In addition, *NuSTAR* solar observations were used to validate the application of the instrument for solar axion searches.

In FY13, improvements to the modeling of the optics response for the NuSTAR telescopes were implemented by refining and upgrading ray-trace simulations for the mission. Specifically, the simulated *NuSTAR* optics response was upgraded by implementing new optical constants derived from latest metrology measurements and by comparing the results to existing raw calibration data. This reduced the discrepancies between the physics-based models and the on-orbit calibration to 10-20%.

X-ray data analysis of high-B radio pulsars in archival *XMM-Newton* and *Chandra* data (Olausen et al. 2013) verified the performance of the initial NS algorithms and yielded the detection of PSR J1734-3333 in X-rays as well as 3σ upper limits on the flux and temperature of two additional objects (PSR B1845− 19, PSR J1001− 5939) supporting the hypothesis that high-B RPPs evolve differently than X-ray-isolated NSs despite their similarities in rotational properties.

First *NuSTAR* observations of NSs were obtained for the magnetar 1E1841-045 in FY13. The analysis of these data together with simultaneous (*Swift*) and archival (*XMM*/*Chandra*) soft X-ray observations revealed the magnetar outflow is consistent with the Beloborodov model (a new model explaining the hard X-ray production in magnetars), and we were able to put new interesting constraints on the geometry of 1E 1841 (An et al. 2013).

In FY14/15, *NuSTAR* conducted additional NS observations. A follow-up observation of the galactic center magnetar SGR J1745-2900, previously discovered by NuSTAR, delivered the first-ever timing information on this object (Kaspi et al. 2014). Interestingly, we observed an increase of the spin-down rate without the indication of a glitch (a sudden spin-up) hinting at a magnetospheric origin of the event.

Our third observation studied the magnetar 1E 2259+586 (Vogel et al. 2014, see Figure 3), which had been only marginally detected in hard X-rays before *NuSTAR*. Our analysis provided the first-ever detection of a pulse profile at energies >20 keV for this source and constrained the PSR geometry using the Beloborodov model mentioned above. We also confirmed the connection between spectral turnover (soft minus hard spectral photon index, Γ_s-Γ_h) and magnetic field as suggested by Kaspi &

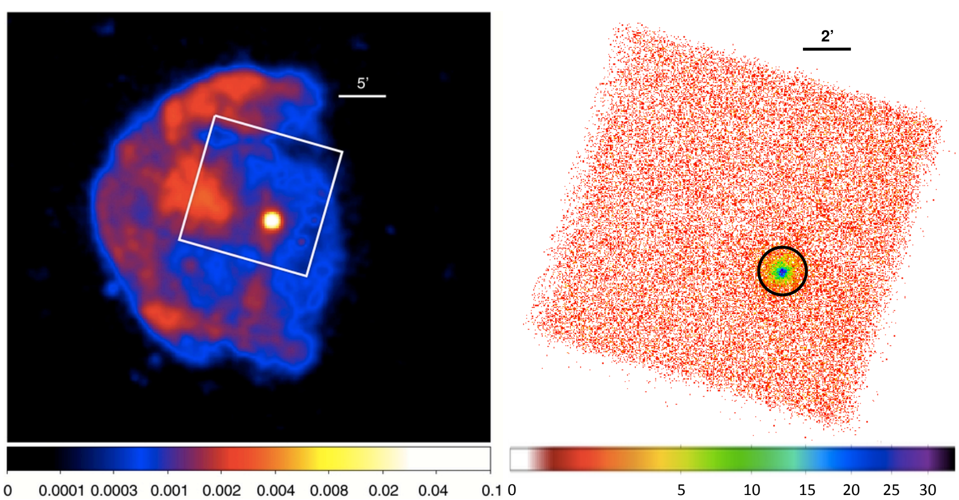

Figure 3 1E 2259+586 located in SNR CTB 109. Left: *ROSAT* image for energies from 0.1-2.4 keV. The white frame indicates the *NuSTAR* field of view and the bright point source is the magnetar 1E 2259+586. Right: Unsmoothed, exposure-corrected *NuSTAR* data in the energy range of 4-79 keV.

Boydstun (2010) and shown in Figure 4, where the red star indicates our result.

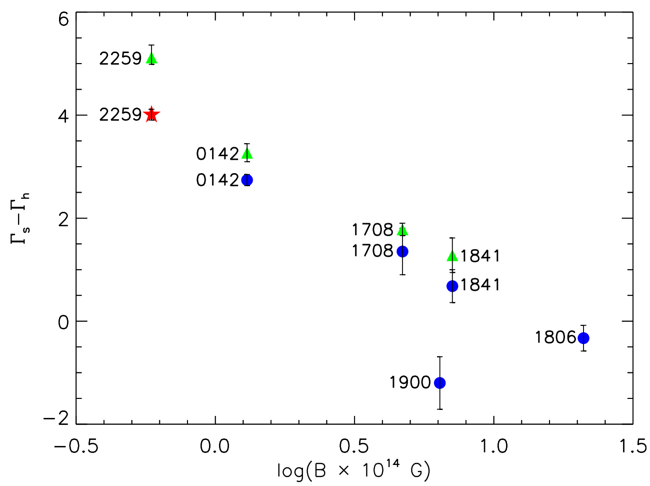

Figure 4 Spectral turnover (Γ_s-Γ_h) vs. magnetic field from Kaspi & Boydstun (2010) including our new result (red star). For details see Vogel et al (2014).

The fourth *NuSTAR*-observed NS object was Geminga, an RPP with a PWN, and these data yielded the first-ever detection of this object in hard X-rays (>10 keV) revealing that there is no simple multi-wavelength spectrum able to describe the pulsar over different energy ranges due to a spectral hardening above 5 keV and a spectral flattening between optical and X-rays (Mori et al. 2014).

Our latest *NuSTAR* observation (1E 1048.1-5937) yielded a clear detection of this magnetar's persistent emission up to 20 keV (Yang et al. 2015). We detect a new feature in the spectrum, i.e. a previously unreported small secondary peak in the average pulse profile (7-10 keV), which grows in amplitude with energy and is likely transient. In contrast to other magnetars, there is no evidence for the spectral turn-up near 10 keV. The absence of a significant turn-up is consistent with observations from a particularly active subset of magnetars having high spin-inferred magnetic fields.

In addition, to our *NuSTAR* NS program we participated in first solar observations. While the primary goal of these solar data is the search for nanoflares able to address the coronal heating problem, these observations can also be used to lay the foundation for solar axion searches (Grefenstette et al. 2015). Axions would be produced in the solar core and could convert into X-rays in the magnetic fields of the photosphere resulting in an excess of X-rays in the center of the solar disk. By definition (axions were initially postulated to solve a problem in QCD) these particles could account for part or all of the dark matter in the universe. We use the first *NuSTAR* solar data to determine the best conditions for a dedicated, future axion observation and work towards first upper limits on the axion-to-photon coupling constant for hadronic axion-models.

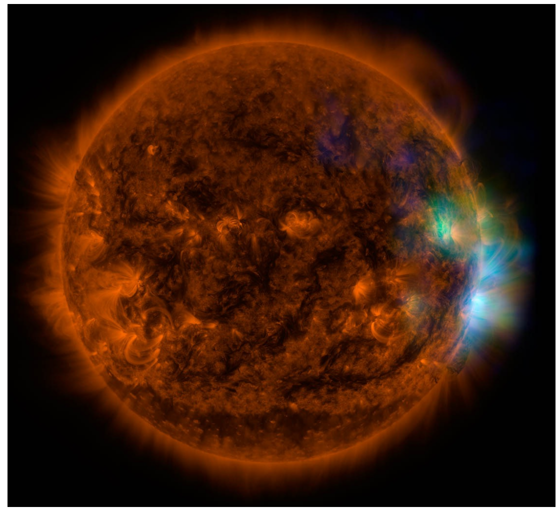

Figure 5 Image of the Sun combining hard X-ray data (NuSTAR) in blue, soft X-rays observations (Hinode) in green, and extreme UV data (Solar Dynamic Observatory, SDO) in yellow and red.
Credits: NASA/JPL-Caltech/GSFC/JAXA

Impact on Mission

Participation in space science is a crucial element in the Laboratory's cyber and space security and intelligence strategic mission thrust. LLNL's ability to provide next generation capabilities for security of space requires a trained workforce that demonstrated excellence in conceiving, fabricating, and performing science with advanced instrumentation. Our analysis of NuSTAR observations of NSs supported re-establishing the Laboratory's pre-imminence in X-ray astronomy and further strengthened LLNL's core competence in high-energy astrophysics. Experience with X-ray optics our team gained through this project is also relevant to high-energy-density physics and the development of laser diagnostics and advanced energy systems.

Conclusion

Discoveries during the last 20 years have revealed new manifestations of NSs and shown that our understanding of these important astrophysical objects is still limited. X-ray observations are crucial for unraveling the complex nature of NSs, and with NASA's *NuSTAR*, we were able to conduct sensitive observations in the hard X-ray band for the first time. The LDRD team's work in developing and characterizing *NuSTAR's* focusing optics and our previous work on NSs provided LLNL with a unique opportunity and we made important contributions to this cutting-edge research field. Additional data from *NuSTAR* and the soon-to-be-launched JAXA *Astro-H* mission will further our understanding of NSs and the Lab is well positioned to analyze these data as well as lead the development of future X-ray optics for a "super" NuSTAR type observatory, the X-ray Surveyor, NNSA diagnostics and axion searches.

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